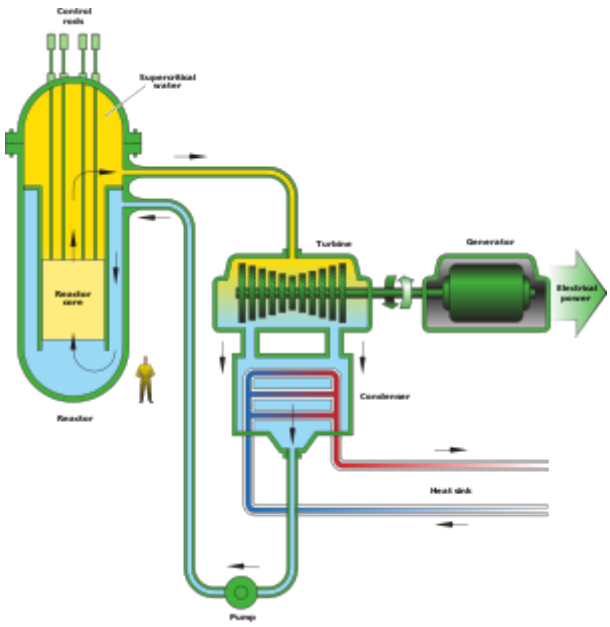
Supercritical water reactor

The **supercritical water reactor** (**SCWR**) is a concept Generation IV reactor,[1] mostly designed as light water reactor (LWR) that operates at supercritical pressure (i.e. greater than 22.1 MPa). The term *critical* in this context refers to the critical point of water, and must not be confused with the concept of criticality of the nuclear reactor.



Supercritical water reactor scheme.

The water heated in the reactor core becomes a supercritical fluid above the critical temperature of 374 °C, transitioning from a fluid more resembling liquid water to a fluid more resembling saturated steam (which can be used in a steam turbine), without going through the distinct phase transition of boiling.

In contrast, the well-established pressurized water reactors (PWR) have a primary cooling loop of liquid water at a subcritical pressure, transporting heat from the reactor core to a secondary cooling loop, where the steam for driving the turbines is produced in a boiler (called the steam generator). Boiling water reactors (BWR) operate at even lower pressures, with the boiling process to generate the steam happening in the reactor core.

The supercritical steam generator is a proven technology. The development of SCWR systems is considered a promising advancement for nuclear power plants because of its high thermal efficiency (~45 % vs. ~33 % for current LWRs) and simpler design. As of 2012 the concept was being investigated by 32 organizations in 13 countries.[2]

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History

The super-heated steam cooled reactors operating at subcritical-pressure were experimented with in both Soviet Union and in the United States as early as the 1950s and 1960s such as Beloyarsk Nuclear Power Station, Pathfinder and Bonus of GE's Operation Sunrise program. These are not SCWRs. SCWRs were developed from the 1990s onwards.[3] Both a LWR-type SCWR with a reactor pressure vessel and a CANDU-type SCWR with pressure tubes are being developed.

A 2010 book includes conceptual design and analysis methods such as core design, plant system, plant dynamics and control, plant startup and stability, safety, fast reactor design etc.[4]

A 2013 document saw the completion of a prototypical fueled loop test in 2015.[5] A Fuel Qualification Test was completed in 2014.[6]

A 2014 book saw reactor conceptual design of a thermal spectrum reactor (Super LWR) and a fast reactor (Super FR) and experimental results of thermal hydraulics, materials and material-coolant interactions.[7]

Design

Moderator-coolant

The SCWR operates at supercritical pressure. The reactor outlet coolant is supercritical water. Light water is used as a neutron moderator and coolant. Above the critical point, steam and liquid become the same density and are indistinguishable, eliminating the need for pressurizers and steam generators (PWR), or jet/recirculation pumps, steam separators and dryers (BWR). Also by avoiding boiling, SCWR does not generate chaotic voids (bubbles) with less density and moderating effect. In a LWR this can affect heat transfer and water flow, and the feedback can make the reactor power harder to predict and control. Neutronic and thermal hydraulic coupled calculation is needed to predict the power distribution. SCWR's simplification should reduce construction costs and improve reliability and safety. A LWR type SCWR adopts water rods with thermal insulation and A CANDU type SCWR keeps water moderator in a Calandria tank. A fast reactor core of the LWR type SCWR adopts tight fuel rod lattice as a high conversion LWR. The fast neutron spectrum SCWR has advantages of a higher power density, but needs plutonium and uranium mixed oxides fuel which will be available from reprocessing.

Control

SCWRs would likely have control rods inserted through the top, as is done in PWRs.

Material

The conditions inside an SCWR are harsher than those in LWRs, LMFBRs, and supercritical fossil fuel plants (with which much experience has been gained, though this does not include the combination of harsh environment and intense neutron radiation). SCWRs need a higher standard of core materials (especially fuel cladding) than either of these. R&D focuses on:

- The chemistry of supercritical water under radiation (preventing stress corrosion cracking, and maintaining corrosion resistance under neutron radiation and high temperatures)
- Dimensional and microstructural stability (preventing embrittlement, retaining strength and creep resistance also under radiation and high temperatures)

- Materials that both resist the harsh conditions and do not absorb too many neutrons, which affects fuel economy

Advantages

- Supercritical water has excellent heat transfer properties allowing a high power density, a small core, and a small containment structure.
- The use of a supercritical Rankine cycle with its typically higher temperatures improves efficiency (would be ~45 % versus ~33 % of current PWR/BWRs).
- This higher efficiency would lead to better fuel economy and a lighter fuel load, lessening residual (decay) heat.
- SCWR is typically designed as a direct-cycle, whereby steam or hot supercritical water from the core is used directly in a steam turbine. This makes the design simple. As a BWR is simpler than a PWR, a SCWR is a lot simpler and more compact than a less-efficient BWR having the same electrical output. There are no steam separators, steam dryers, internal recirculation pumps, or recirculation flow inside the pressure vessel. The design is a once-through, direct-cycle, the simplest type of cycle possible. The stored thermal and radiologic energy in the smaller core and its (primary) cooling circuit would also be less than that of either a BWR's or a PWR's.[8]
- Water is liquid at room temperature, cheap, non-toxic and transparent, simplifying inspection and repair (compared to liquid metal cooled reactors).
- A fast SCWR could be a breeder reactor, like the proposed Clean And Environmentally Safe Advanced Reactor, and could burn the long-lived actinide isotopes.
- A heavy-water SCWR could breed fuel from thorium (4x more abundant than uranium), with increased proliferation resistance over plutonium breeders.

Disadvantages

- Lower water inventory (due to compact primary loop) means less heat capacity to buffer transients and accidents (e.g. loss of feedwater flow or large break loss-of-coolant accident) resulting in accident and transient temperatures that are too high for conventional metallic cladding.[9]

However, Safety analysis of LWR type SCWR showed that safety criteria are met at accidents and abnormal transients including total loss of flow and loss of coolant accident.[9]:97,104 No double ended break occurs because of the once-through coolant cycle. Core is cooled by the induced flow at the loss of coolant accident.

- Higher pressure combined with higher temperature and also a higher temperature rise across the core (compared to PWR/BWRs) result in increased mechanical and thermal stresses on vessel materials that are difficult to solve. A LWR type design, reactor pressure vessel inner wall is cooled by the inlet coolant as a PWR. Outlet coolant nozzles are equipped with thermal sleeves. A pressure-tube design, where the core is divided up into smaller tubes for each fuel channel, has potentially fewer issues here, as smaller diameter tubing can be much thinner than massive single pressure vessels, and the tube can be insulated on the inside with inert ceramic insulation so it can operate at low (calandria water) temperature.[10]

The coolant greatly reduces its density at the end of the core, resulting in a need to place extra moderator there. A LWR type SCWR design adopts water rods in the fuel assemblies. Most designs of CANDU type SCWR use an internal calandria where part of the feedwater flow is guided through top tubes through the core, that provide the added moderation (feedwater) in that region. This has the added advantage of being able to cool the entire vessel wall with feedwater, but results in a complex and materially demanding (high temperature, high temperature differences, high radiation) internal calandria and plena arrangement. Again a pressure-tube design has potentially

fewer issues, as most of the moderator is in the calandria at low temperature and pressure, reducing the coolant density effect on moderation, and the actual pressure tube can be kept cool by the calandria water.[10]

- Extensive material development and research on supercritical water chemistry under radiation is needed
- Special start-up procedures needed to avoid instability before the water reaches supercritical conditions. Instability is managed by power to coolant flow rate ratio as a BWR.
- A fast SCWR needs a relatively complex reactor core to have a negative void coefficient. But single coolant flow pass core is feasible.

See also

- Generation IV reactor
- Breeder reactor
- Reduced moderation water reactor, a concept that is in some ways similar and in others overlapping to the SCWR concept, and is under development apart from the Generation IV program.
- Generation III reactor
  - Advanced Boiling Water Reactor (ABWR)
  - Economic Simplified Boiling Water Reactor (ESBWR) (generation III+)

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- INL SCWR page (https://web.archive.org/web/20100422134942/http://nuclear.inl.gov/gen4/scwr.shtml)
- INL presentation (https://www.webharvest.gov/peth04/20041015183645/http://gif.inel.gov/roadmap/pdfs/supercritical-water-cooled_reactor.pdf)
- INL Progress Report for the FY-03 Generation-IV R&D Activities for the Development of the SCWR in the U.S. (https://web.archive.org/web/20060620115029/http://nuclear.inl.gov/gen4/docs/scwr_annual_progress_report_gen-iv_fy-03.pdf)
- Generation IV International Forum SCWR website (https://web.archive.org/web/20060218062110/http://www.gen-4.org/Technology/systems/scwr.htm).
- INL SCWR workshop summary (https://web.archive.org/web/20071129121653/http://neri.inel.gov/program_plans/pdfs/appendix_2.pdf)

External links

- Idaho National Laboratory Supercritical-Water-Cooled Reactor (SCWR) Fact Sheet (https://web.archive.org/web/20130215115826/http://www.inl.gov/research/supercritical-water-cooled-reactor/)
- UW presentation: SCWR Fuel Rod Design Requirements (http://wins.engr.wisc.edu/research/scw/intl/SCIEM-III/SCW-INEL-Cor-Des-Crit.ppt) (PowerPoint presentation).
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